

We are witnessing a rapid development of computing technologies, increasingly integrating various aspects of our lives. This progress is accompanied by significant advancements in optoelectronics, a field that encompasses electronic devices capable of emitting, absorbing, or modifying light signals. Among these devices, semiconductor lasers play a crucial role in modern technologies. They are easily integrated with electronic systems and find applications in telecommunications, measurement systems, medicine, LiDAR technology used in autonomous vehicles, and consumer electronics. The semiconductor laser market, valued at approximately \$9 billion in 2023, is growing at an annual rate of over 7%, driven by these technological advancements.

In recent years, particular attention has been drawn to VCSELs (Vertical-Cavity Surface-Emitting Lasers), which emit light perpendicular to the surface of the device. VCSELs offer unique advantages, including the ability to create two-dimensional arrays, ease of testing and production, and high beam quality. These lasers are experiencing a technological boom and are increasingly used in facial recognition in smartphones, three-dimensional sensing systems, augmented and virtual reality (AR/VR) technologies, and optical communication systems.

To increase the emitted power of a VCSEL, the area where laser radiation is generated, known as the aperture, can be enlarged. This aperture is typically circular, reflecting the cylindrical symmetry commonly employed in VCSEL designs. However, enlarging the aperture results in the emission of higher-order modes, reducing the quality of the emitted beam. A mode, in the context of a laser, refers to how electromagnetic waves propagate inside the laser cavity, creating a specific intensity distribution of light at a well-defined wavelength. Very large apertures exacerbate this issue, leading to the emergence of whispering-gallery modes, where the optical field is concentrated near the aperture's edges. This results in inefficient cavity utilization, limited output power, and reduced device efficiency.

The goal of our project is to overcome this limitation by designing and fabricating VCSELs with aperture shapes inspired by research on wave chaos. Instead of traditional circular apertures, we will develop devices with asymmetric shapes, such as D-shaped, stadium-shaped, or other entirely asymmetric geometries. These changes will allow for better mode distribution within the laser cavity, increased output power, and improved spatial uniformity of the emitted light. Additionally, we aim to investigate how designing subsequent epitaxial layers of the laser to favor the excitation of a greater number of modes can further enhance these properties.

Our research will have broad applications in LiDAR technology, optical coherence tomography (OCT), AR/VR systems, and high-uniformity lighting. It may also contribute to the development of optical neural networks and advanced optical data transmission systems. The project will be carried out by a team of researchers from Lodz University of Technology, Łukasiewicz – Institute of Microelectronics and Photonics, and Wrocław University of Science and Technology. By combining advanced computer simulations, precise epitaxial growth, modern technological processes, and detailed experimental characterization of the fabricated lasers, our project aims to revolutionize VCSEL design, laying the foundation for next-generation optoelectronic technologies.